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EFFECTS OF TEMPERATURE CHANGES ON THE OUTPUT OF TIME-INTEGRATING CORRELATORS

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DEFENCE RESEARCH ESTABLISHMENT OTTAWA
TECHNICAL NOTE 93-30

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Electronic Support Measures Section
Electronic Warfare Division

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ABSTRACT

This technical note presents an analysis of the effects of temperature changes on the output correlation peak of a time-integrating correlator. Temperature fluctuations cause changes in the acoustic velocity in Bragg cells and important alterations of the format of the output. The relation between the temperature and the changes in acoustic velocity, the amplitude of the output correlation peak and the measurements of the difference of time-of-arrival of the input signals are analyzed for two different formats of the output. For the first format, when the output does not contain fringes before changing the temperature, a temperature control within 0.089°C is required to limit the fluctuation of the amplitude of the output peak to less than 10%. In the second case, with an optimal multi-fringe pattern, the detection of a correlation peak is resistant to temperature changes. To avoid errors in the measurement of the time-difference-of-arrival, a temperature control within 5.4°C is required.

RÉSUMÉ

Cette note technique présente une analyse des effets des fluctuations de température sur la sortie d'un corrélateur à intégration temporelle. Ces fluctuations produisent des changements de vitesse des ondes acoustiques dans les cellules de Bragg et le format de la sortie en est grandement altéré. Les dépendances entre les changements de température et de vitesse acoustique, l'amplitude du pic de corrélation et les mesures de la différence de temps d'arrivée des signaux d'entrée y sont analysées pour deux différents formats du signal de sortie. Le premier format ne contient pas de franges avant le changement de température. On conclut que les changements de température ne doivent pas excéder 0.089° C pour limiter à 10% les fluctuations d'amplitude du pic de sortie dans ce cas. Dans le deuxième cas la détection du pic de corrélation avec un système de franges optimisé n'est pas sensible aux changements de température. Il est possible d'éviter les erreurs de mesure des différences de temps d'arrivée en limitant les fluctuations de température à 5.4°C.

EXECUTIVE SUMMARY

It has previously been demonstrated that acousto-optic spectrum analysers built with one Bragg cell are sensitive to temperature changes, thus requiring strict temperature control if the output specifications are to be maintained within reasonable limits. These results suggest that more complex interferometric structures such as Time-Integrating Correlators (TIC)s that contain two Bragg cells could be even more sensitive to temperature fluctuations.

This technical note presents an analysis of the effects of temperature changes on the output correlation peak of a time-integrating correlator. Temperature fluctuations cause changes in the acoustic velocity in Bragg cells and important alterations of the format of the output.

The first effect considered is the changes of the correlation peak amplitude resulting from alterations of the output format: two different output formats are considered. The first one is commonly used and does not contain any fringe pattern. It is found to be very sensitive to temperature changes. For example, calculations demonstrated that a temperature variation of less than 0.089°C is required to limit the fluctuation of the amplitude of the output peak of a TIC to less than 10%. The second format contains a multi-fringe pattern having an optimal number of fringes. Our calculations demonstrated that this proposed format is significantly less sensitive to temperature change.

The other effect considered is the impact of changes in acoustic velocity on measurements of the time-difference-of-arrival. To avoid errors in the measurement of the time difference of arrival, the analysis predicts that a temperature variation of less than 5.4°C is required.

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LIST OF ABBREVIATIONS

TIC:	Time-Integrating Correlator
RF:	Radio Frequency

1.0 INTRODUCTION

Acousto-optic spectrum analysers containing one Bragg cell are used for the analysis, in an electronic warfare context, of radar emissions. It has recently been demonstrated [1] that they are sensitive to temperature changes and require strict temperature control to maintain the registration stability of their output. These results suggest that the effect of temperature changes on the performance of more complex interferometric systems such as Time-Integrating Correlators (TIC)s using two Bragg cells could be significant.

This technical note presents an analysis of the effects of temperature changes in the Bragg cells on the output correlation peak of a time-integrating correlator. Such temperature fluctuations cause changes in the acoustic velocity in the Bragg cells and important alterations of the format of the output. Other effects of temperature changes, such as expansion or contraction of the materials used to build the TIC, are not considered here. Two specific parameters of the output of the TIC are considered here: (a) the peak amplitude changes resulting from alterations of the output format; and, (b) possible peak positioning errors in the measurement of the time-difference-of-arrival of the Radio Frequency (RF) input signals.

This technical note is structured as follows. Section 2.0 contains a brief description of the operation of a TIC with emphasis on the aspects that are affected by temperature changes. Section 3.0 contains the description of a computer simulation of the output of a TIC. The input parameters and the format of the results produced by the simulation are discussed. Section 4.0 presents an analysis of the effect of temperature changes for different initial settings of the TIC. The cases with no fringe or with an optimal fringe pattern before the temperature change are discussed. Section 5.0 contains an analysis of the effects of temperature changes on time-difference-of-arrival measurements performed by a TIC. The results obtained in the previous sections are summarized in Section 6.0.

2.0 OPERATION OF A TIME-INTEGRATION CORRELATOR

The acousto-optic interferometric TIC is designed to perform the correlation of two one-dimensional signals. TICs can be used for applications such as the processing of RF spread spectrum signals [2] or the rapid search of large data bases like those used in DNA analysis [3]. The many possible ways to build TICs are well documented in the literature [2,4]. A schematic diagram of a typical interferometric implementation using two Bragg cells is illustrated in Figure 1 and is used for the rest of the discussion.

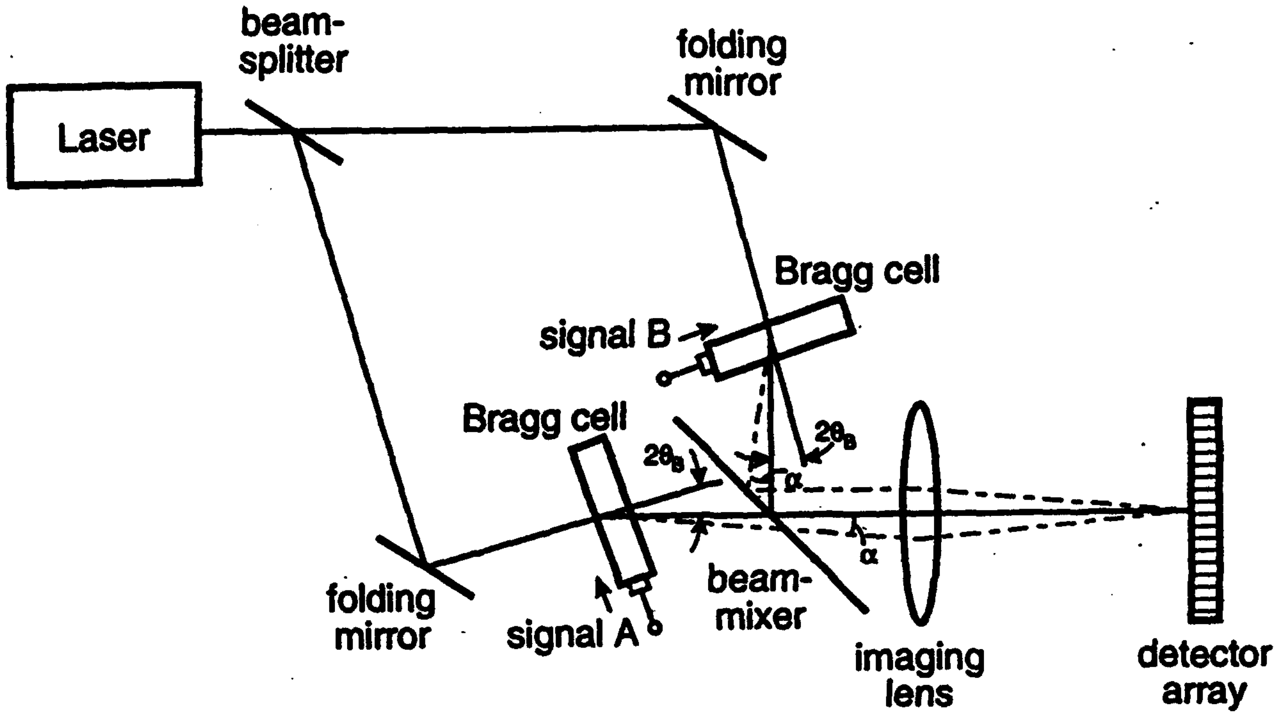

Figure 1: Geometry of the diffracted rays at temperature T (solid line) and at temperature T+ΔT (dotted line) for a signal with a carrier frequency f_c at the center frequency f_T of the TIC.

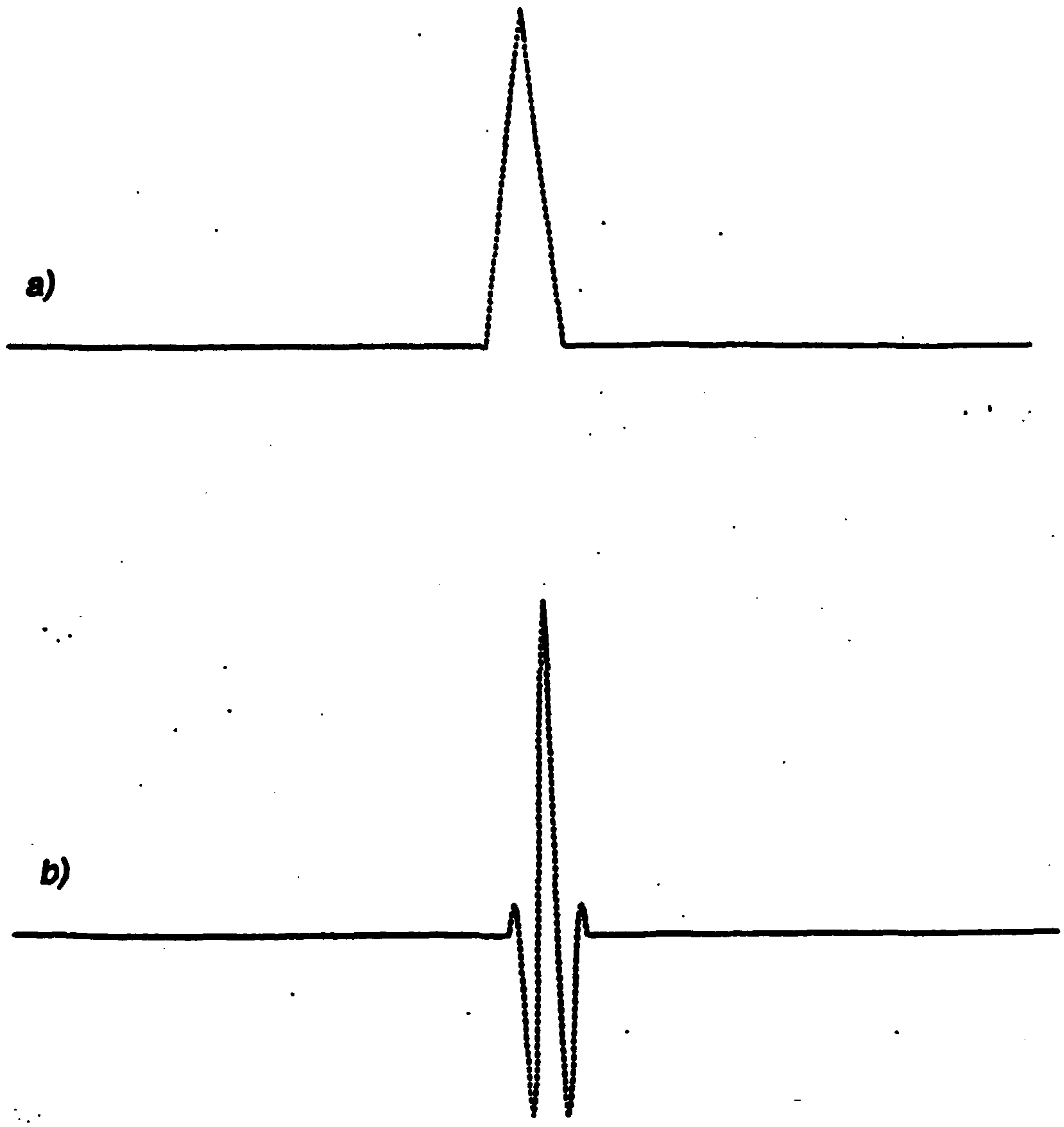

Figure 2: Format of the output of a TIC when the centre frequency f_T of the TIC coincides with the carrier frequency f_c of the signal: (a) at temperature T; and, (b) at temperature T+ΔT.

Figure 1 illustrates a typical situation where two RF spread spectrum signals are applied to Bragg cells A and B of a TIC. The light diffracted by the Bragg cells contains the data modulated onto the RF input signals. The resulting correlation peak is formed [2] due to time integration by the detector array of the images of the signals propagating in the Bragg cells. A detailed mathematical description of the operation of TICs can be found in [2] but will not be repeated here.

Let us consider a TIC aligned at temperature T and operating at a RF centre frequency f_T. When the carrier frequency of the input signals f_c is matched to the centre frequency f_T of the TIC, the two flat wavefronts diffracted by the Bragg cells propagate in the same direction, as illustrated in Figure 1 (the solid line after the beam mixer). The output is the product of a uniform illumination that can be considered as a fringe system with an infinite period, and a triangular envelope whose location on the detector depends on the time-difference-of-arrival of the input signals (see Figure 2a). The intensity of the diffracted light illuminating the detector depends on the relative phase difference between the interfering wavefronts. It can be adjusted to a maximum by tuning the relative phase of the RF input signals. This light distribution is detected and integrated over time by a linear array of light detectors. The pedestal is removed using the technique described in [2]. The amount of energy collected by each detector depends on the location of the element relative to possible fringes of the light distribution produced by the TIC.

3.0 SIMULATION OF THE OUTPUT OF A TIME-INTEGRATING CORRELATOR

The study of the data collection process of a TIC [5] is particularly interesting because of the many different output configurations that are possible and of the highly varying performances that are associated with them. Some of these configurations have a potential for very high performance but, unfortunately, the quality of these outputs is unstable: they may produce the best results but they also may produce the worst ones if very strict conditions of operation are not maintained.

However, it is possible to find a data collection technique where the degradation associated with the data collection process is acceptable as well as resistant to changes in environmental conditions and to the presence of aberrations. These results were obtained from a computer simulation of the detection process of a TIC and are fully documented in [5].

The computer model was developed to study the measured amplitude of the correlation peak as a function of the various output parameters of the TIC. The output is the product of a fringe system with a variable period and of a triangular envelope whose location on the detector depends on the time-difference-of-arrival of the input signals. The parameters (see Figure 3) are W,

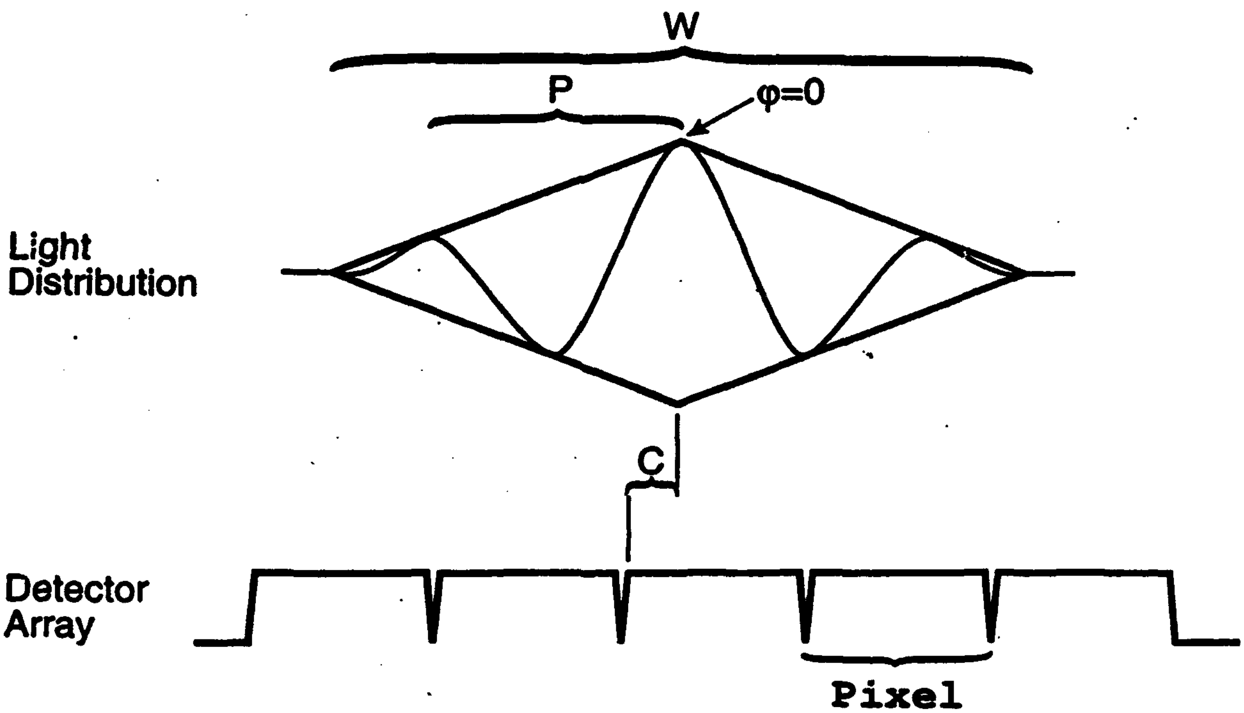

Figure 3: Definition of the input parameters for the computer simulation.

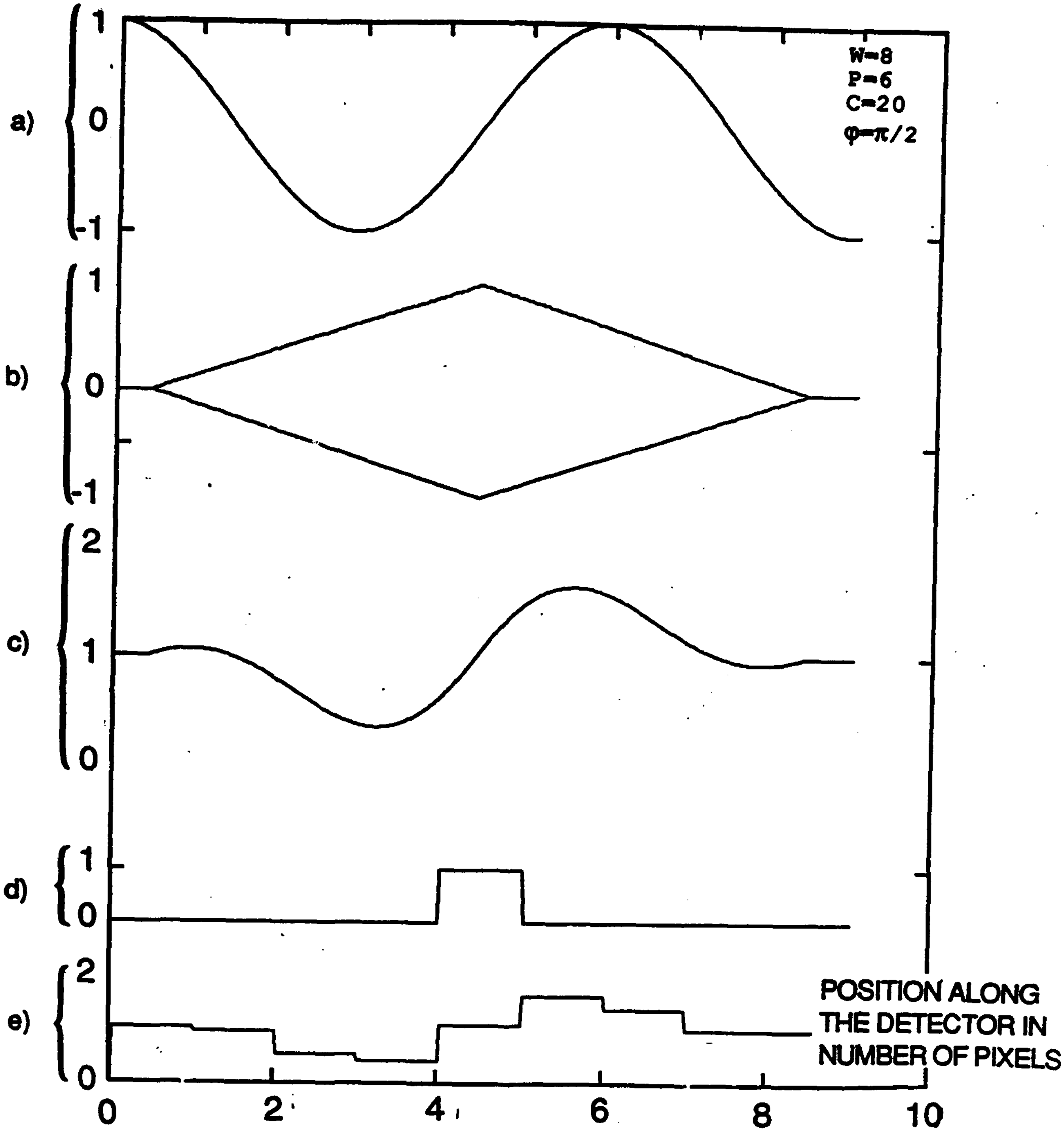

Figure 4: One typical output from the simulation. From top to bottom, the first row illustrates the fringe pattern. The second row illustrates the triangular envelope and the third row displays the product of the first two rows added to a uniform bias of amplitude one. The forth row illustrates the position of the detecting elements of the array and their sensitivity response. The last row presents the histogram of the energy collected by each element.

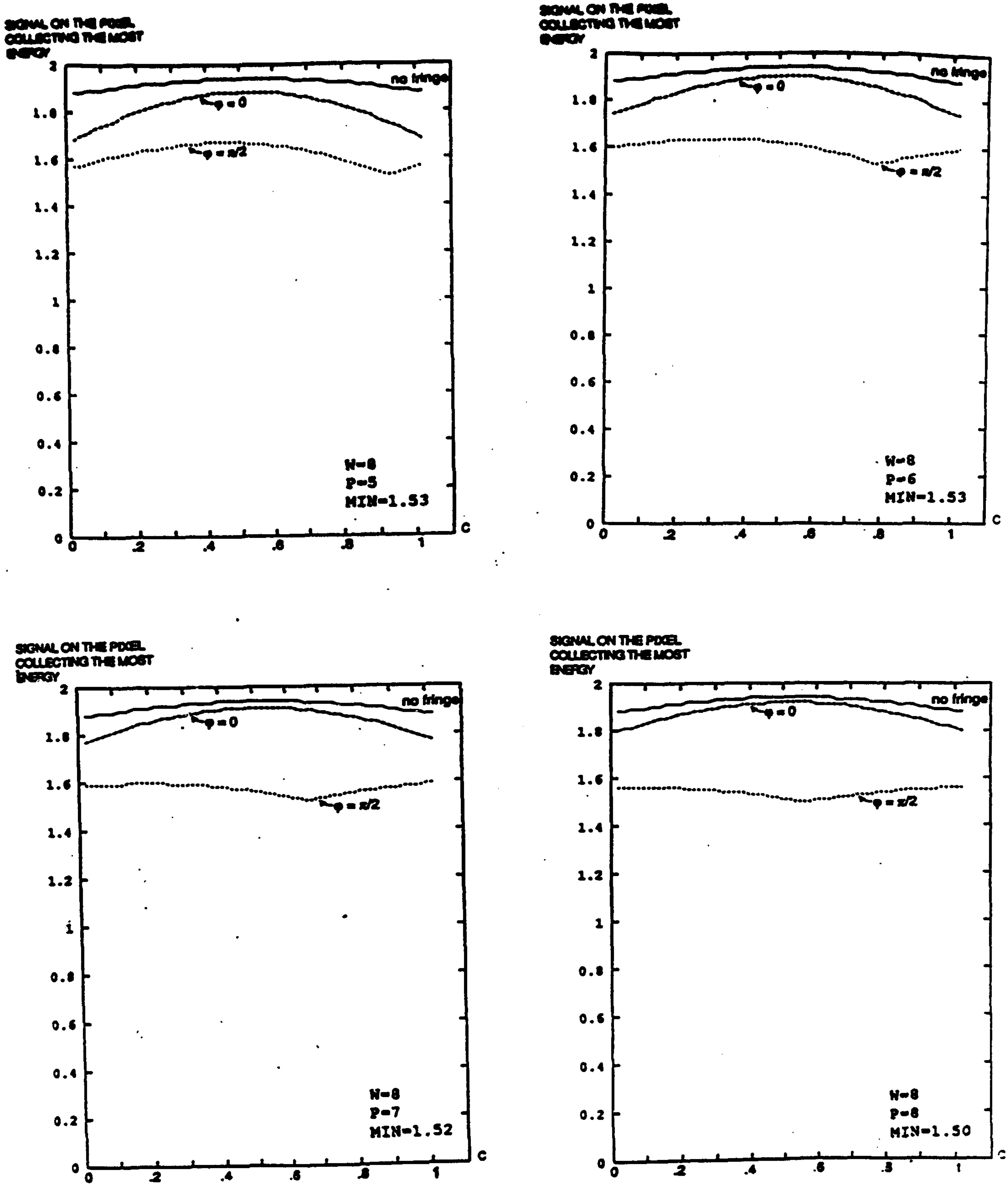

Figure 5: Plot of the value of the intensity on the element collecting the most energy for all positions c of the apex of the triangular envelope relative to the detector array, for the signal specified by the user.

the width of the triangular envelope at the base, P, the period of the fringe pattern, ϕ, the phase of the fringe pattern at the apex of the triangular envelope, and C, the location of the detecting elements relative to the apex of the triangular envelope. All these parameters are defined in units of number of pixels where a pixel is one element of the detector array. The simulation also includes the capability to use different sensitivity profiles for the detecting elements.

Figure 4 illustrates one of the two typical outputs from the simulation. From top to bottom, the first row illustrates the fringe pattern whose amplitude oscillates between -1 and +1. The second row illustrates the triangular envelope whose minimum and maximum amplitude are respectively -1 and +1 and the third row displays the product of the first two rows added to a uniform bias of amplitude one. The fourth row illustrates the position of the detecting elements of the array and their ideal or measured sensitivity response. The last row presents the energy collected by each element.

Figure 5 illustrates the other type of drawing produced by the simulation where the value of the intensity on the element collecting the most energy is calculated for all positions of the apex of the triangular envelope relative to the detector array, for the signal specified by the user. The required input parameters are the width W of the base of the triangular envelope in number of pixels and the period P of the fringe pattern in number of pixels. The calculations are done for $\phi = 0$ and $\phi = \pi/2$ that have been found to be, respectively the best and the worst case for the detection of a peak. It also calculates, for comparison purposes, what would be the maximum reading on the detector array if there was no fringe and if the phase difference between the input signals was optimized to obtain the strongest signal. This last case produces the highest peak amplitude. Figure 5 illustrates four such drawings for W=8 and p=5, 6 ,7 and 8. The higher curve corresponds to the case with no fringe while the middle and lower curve correspond respectively to $\phi = 0$ and $\phi = \pi/2$ with a fringe pattern. The triangular envelope specified by the operator was used for all cases.

4.0 EFFECTS OF TEMPERATURE CHANGES ON THE AMPLITUDE OF THE PEAK

In an ideal condition, the output of a perfectly aligned TIC with no aberration is the product of a triangular envelope with a uniform background and no fringe is present. If the temperature fluctuates, the acoustic velocity within the Bragg cell crystal changes thus modifying the diffraction angles of the two wavefronts. The same temperature changes is assumed for both Bragg cells. They consequently propagate, after the beam mixer, at an angle α (see Figure 1) and the period of the fringe system generated by the interference of these two beams is a function of the angle between the two beams. The output light distribution is

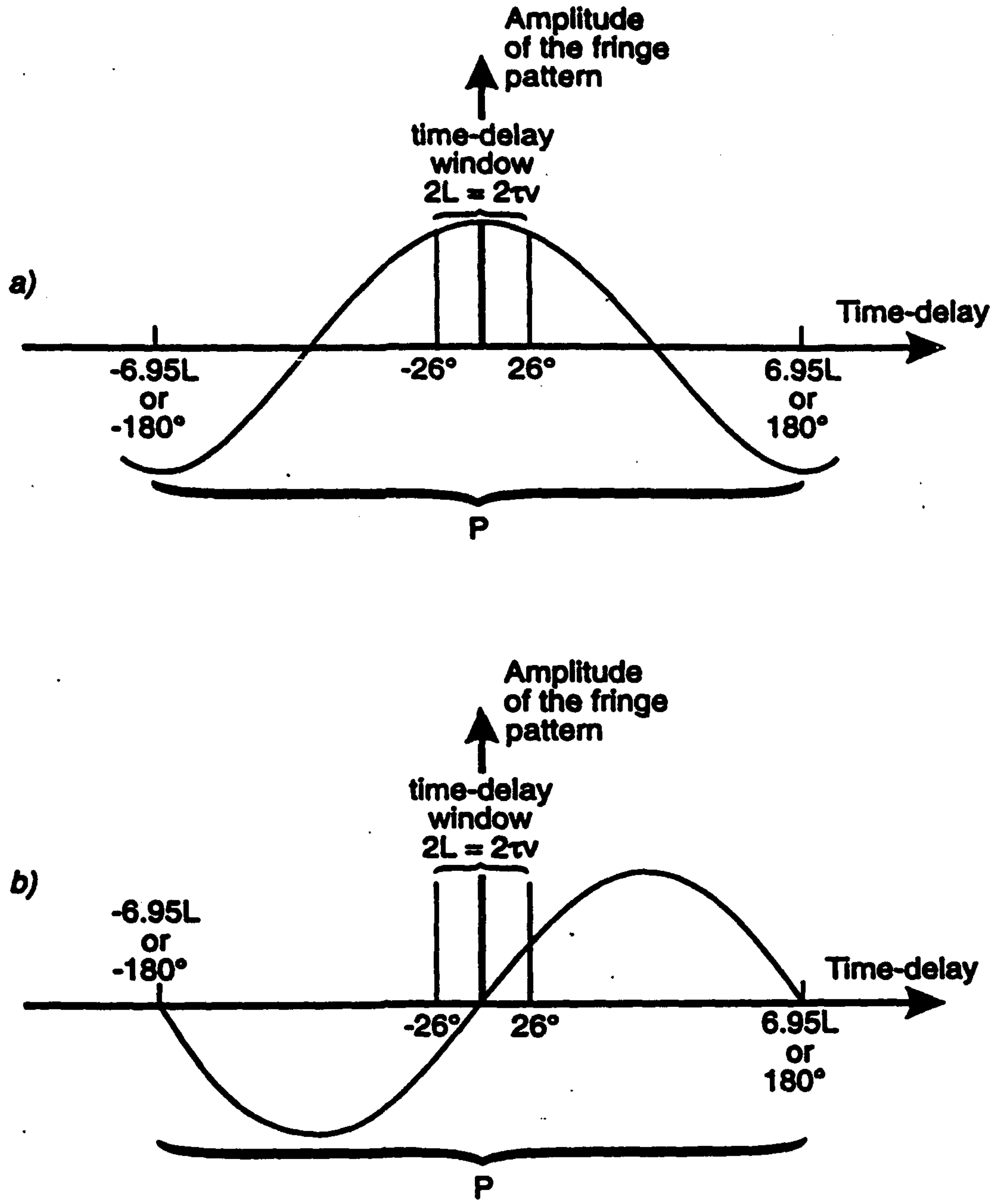

Figure 6: (a) Condition for a 10% amplitude drop at the edge of the time-delay window;
(b) Situation when the fringe pattern has a null in the middle of the time-delay window.

then the product of the fringe system (with a finite period) with a triangle envelope whose location depends on the time difference of arrival of the input signals (see Figure 2b). The format of the output has thus been significantly modified and it will be demonstrated that the stability of the measured amplitude of the correlation peak may be compromised.

If the correlator is build in such way as to produce vertically polarized diffracted light, the capability of the two beams to interfere when they are propagating at an angle α is not affected because the optical vectors of the two beams are still parallel. When other polarizations are used, the optical vectors of the diffracted beams are no longer exactly parallel when they propagate at an angle α. However, the effect on the capability of the two beams will be negligible if the angle α is small. It is generally the case for the small bandwidth TICs used for the processing of spread spectrum communication signals. It is interesting to note that no rotation of the optical vector has been reported by Dimmick et al. in their study of the effects of temperature changes on the type of TeO_2 Bragg cells generally used to build TIC.

The following methodology is used to study the effect of temperature change on the measured amplitude of the correlation peak. It is assumed first that the TIC output had initially no fringe but that a fringe pattern results from the temperature change. The cases of a maximum or a null of the fringe pattern located in the middle of the time delay window are successively considered. In the second part, the fringe pattern with an optimal period (determined from the simulation) is used and the effects of temperature changes are calculated.

4.1 Initial Condition: No Fringe Before the Temperature Change

A correlation peak with no fringes is obtained: (a) when the carrier frequency of the input signals f_c is matched to the centre frequency f_T of the TIC; and, (b) when there are no optical aberrations or misalignments in the optical system. Thus the two flat wavefronts diffracted by the Bragg cells propagate in the same direction, as illustrated in Figure 1 (the solid line after the beam mixer). Furthermore, the output is the product of a uniform illumination that can be considered as a fringe system with infinite period, and a triangular envelope whose location on the detector depends on the time difference-of-arrival of the input signals (see Figure 2a).

4.1.1 When a Maximum of the Fringe Pattern is in the Middle of the Time-Delay Window

The presence of a maximum of the fringe pattern within the time-delay window of a TIC constitutes the most favourable situation for the detection of the peak. Let us consider the particular case where an aberration, a misalignment of some sort or

a previous temperature change have generated a fringe pattern with a maximum in the middle of the time-delay window of the TIC. The location of the fringe pattern is, in practice, unpredictable because it depends on the specific values of the phenomena causing it.

One of the features of the TIC architecture illustrated in Figure 1 is the ability to observe the correlation peak over a time-delay window $2L = 2\tau v$ where L is the length of the Bragg cells in meters, τ is the transit time of the signals in the Bragg cells in seconds and v, in meters/second, is the acoustic velocity. If a 10% drop in peak amplitude at the edge of the time-delay window is allowed (see Figure 3a) the minimum period P of the fringe pattern, expressed as a fraction of the length 2L of the time-delay window, has to meet the following condition (see Figure 6a):

$$P = 2L \times (360^\circ/52^\circ) \tag{1}$$

$$P = 13.9\,L \tag{2}$$

The angle α (see Figure 1, dotted lines) between the diffracted beams that is required to produce a fringe system with a period P is given by [6] using the small angle approximation:

$$\alpha = \lambda/(2P) \tag{3}$$

$$\alpha = \lambda/(27.7L) \tag{4}$$

where λ is the wavelength of the illuminating laser light.

Let us now calculate the velocity change Δv that is necessary to produce the angle α. At temperature T, using the small angle approximation again, the total angle through which the incoming light is diffracted is $2\theta_B$, where $2\theta_B$ is given by [1]:

$$2\theta_B = \lambda f/v \tag{5}$$

from which

$$dv/d(2\theta_B) = -\lambda f/4\theta_B^2 \qquad (6)$$

Substituting for $d(2\theta_B)$ the value of α from Equation 4 and the value of $2\theta_B$ from Equation 5, we obtain

$$dv = -v^2/27.7fL \qquad (7)$$

The following parameters are typical of a TeO_2 Bragg cell operating in the slow shear mode: a center frequency f = 45 MHz, an illumination wavelength λ=633 nm, an acoustic velocity v = 617 m/s and a transit time τ = 50 μs. Substituting in Equation 7 gives:

$$dv \leq -.00989\ m/s \qquad (8)$$

The temperature coefficient of the acoustic velocity for this type of Bragg cell material [1] is 180.6 ppm/°C at 20°C. We can then conclude that a temperature stability of less than 0.089°C is required to ensure that the peak amplitude is not decreased by more than 10% by the changes in acoustic velocity due to temperature changes. Thermal instabilities in Bragg cells can have several causes such as input signal load, high intensity laser illumination and ambient temperature variations.

4.1.2 When a Null of the Fringe Pattern is in the Middle of the Time-Delay Window

We will now consider the worst case for the detection of a correlation peak: when a null of the fringe system is within the time-delay window of the TIC.

As an example, let us consider the fringe system described by Equation 2 with a period P=13.9L when a null happens to be located in the middle of the time-delay window (see Figure 6b). The peak formed by the product of the fringe system with the triangular envelope, could be difficult or impossible to detect on most of the window depending on the detection threshold that is used. This undesirable situation illustrates that not only a good control of the temperature is required, but that the relative phase of the two input signals has to be adjusted to avoid the formation of blind spots in the time-delay window and to maintain the detectability of the peak.

4.2 Initial Condition: Optimal Fringe Pattern Before the Temperature Change

It was demonstrated using the computer simulation described in [5] that with the width W (expressed in number of pixels of the detector array) of the triangular envelope varying between

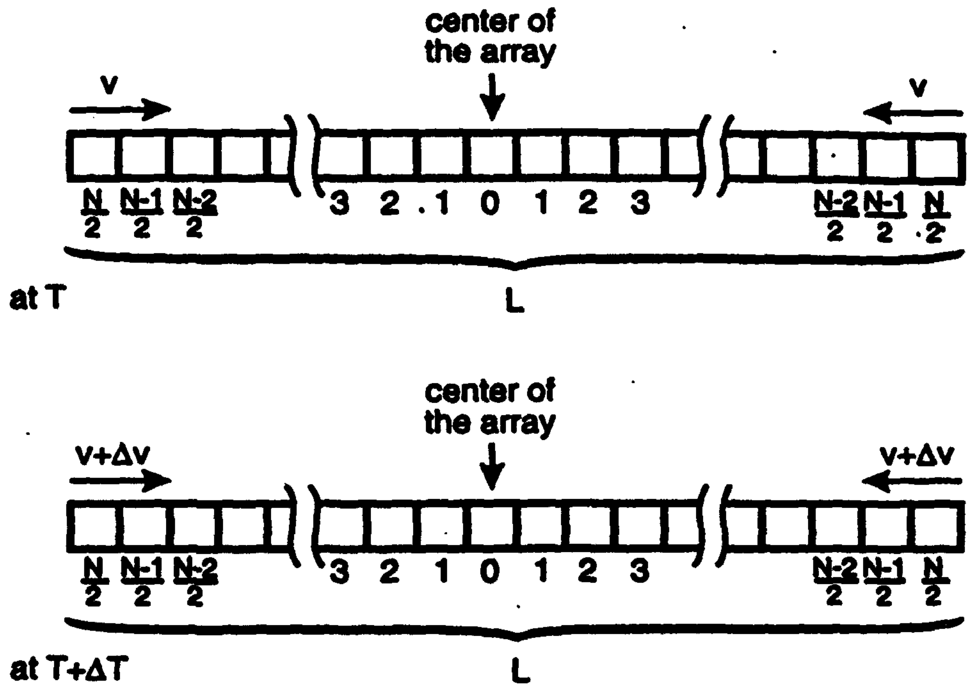

Figure 7: Time-difference-of-arrival measurements of the input signals at T and at T+ΔT.

$$8 < W < 12 \text{ units}$$

and the period P of the fringe varying between

$$5 < P < 8,$$

the minimum amplitude of the detected peak varies between 1.50 and 1.54 (the maximum amplitude being normalized at 2) and is almost independent of the position C of the array of detectors relative to the location of the fringe pattern produced by the TIC (see Figure 6). A minimum detectability of the correlation peak is thus ensured. The dependence on the shape of the response of the detecting element has been demonstrated to be minimal in practice, as long as it is a rough approximation of a rectangular response [5].

In order to assess the temperature sensitivity of the multi-fringe detection process, we now calculate the temperature change required to transform a fringe pattern with a five pixel period into a fringe pattern with a six pixel period. A pixel size of 13 μm is used. It corresponds to the size of the detecting element of the Thompson-CSF TH 7932 board and TH 7841A array used for the construction of our first correlator prototype.

From Equation 3 it can be calculated that the angles between the two beams that produce a fringe period of five and six pixels are respectively, 0.00974 rad. and 0.00811 rad. so an angle difference of 0.00163 rad. changes the fringe period from five to six pixels. From Equation 6 we can calculate that the acoustic velocity change associated with that angle change is 43.58 m/s. Therefore, given a temperature coefficient of the acoustic velocity of 180.6 ppm/°C, a temperature change of 387°C is necessary to increase the period from five pixels to six pixels. This indicates that the multi-fringe detection of the correlation peak is not only a geometrically stable configuration for the measurement of the amplitude of the peak but it is also thermally stable.

5.0 EFFECT OF TEMPERATURE CHANGES ON THE TIME-DIFFERENCE-OF-ARRIVAL MEASUREMENTS

Let us now consider the effect of temperature and acoustic velocity changes on the measurement of the difference of time-of-arrival of the RF input signals. Remembering that it is possible to observe the correlation peak over a time-delay window equal to twice the transit time τ of the signals in the Bragg cells, and that the length of the Bragg cells is L then, if there are N elements in the detector array, the time resolution of each element is 2L/Nv. The difference of time-of-arrival $T_{n,v}$ associated with a particular element n and an acoustic velocity v is (see Figure 7):

$$T_{n,v} = 2Ln/(N+1)v \qquad (9)$$

where n=0 is the central element where the peak is formed when the two input signals arrive simultaneously (see Figure 4). The time resolution associated with a new velocity v+Δv is 2L/(N+1)(v+Δv). If we then define, as a criterion of operation, that the error in the measurement of the difference of time-of-arrival should not exceed one resolution element at the end of the detector array, it follows that:

$$T_{\frac{T}{2},v} = T_{\frac{T}{2}+1,v+\Delta v} \qquad (10)$$

$$\frac{N}{2} \times 2L/(N+1)v \leq (\frac{N}{2}+1) \times 2L(N+1)(V+\Delta v) \qquad (11)$$

and from Equation 11, the velocity change Δv associated with such an error is given by:

$$\Delta v \leq 2v/N \qquad (12)$$

Substituting N = 2048 and v = 617 m/s in Equation 12 gives:

$$\Delta v \leq .6\ m/s \qquad (13)$$

With an acoustic velocity temperature coefficient of 180.6 ppm/°C, a temperature change of 5.4°C is required to produce an error of one time resolution element at the end of the array.

6.0 CONCLUSION

We have demonstrated that the format of the output of a TIC can be dramatically altered by very small temperature changes. An uncontrolled fringe pattern is then generated and blind spots at unknown locations in the time-delay window are likely to result. The first case considered was where no fringe pattern was present before temperature changes were introduced. Thus under this condition, when a maximum of the fringe pattern is located in the middle of the time-delay window of the correlator, temperature control within 0.089°C is required to limit the fluctuation of the amplitude of the output peak of a TIC to less than 10%. If a null of the fringe pattern is located within the time-delay window, blind spots will occur and the detection of the peak will be difficult, if not impossible.

A new data collection technique described in [5] uses an optimal multi-fringe pattern and was developed at DREO to alleviate the problem described in the previous paragraph. It is not sensitive to temperature changes and ensures an acceptable minimum detectability of the output correlation peak.

The condition required to avoid errors in the measurement of the time-difference-of-arrival was defined. The location of a peak with less than one pixel of error requires a temperature control within 5.4°C. The parameters of operation have naturally to be such that the detection of the peak is possible.

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TIME-INTEGRATING CORRELATOR
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